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Do Biofuel Mandates Raise Food Prices?

by

Ujjayant Chakravorty, Marie-Hélène Hubert, Michel Moreaux and Linda Nøstbakken[1]

Abstract

Biofuels have received a lot of attention as a substitute for gasoline in transportation. They have been blamed universally for recent increases in food prices. Both the United States and the European Union have adopted mandatory blending policies that require a sharp increase in their use. Many studies have shown that these energy mandates may have a large (30-60%) impact on food prices. We develop a model that takes into account that with rising incomes, people, especially in the developing world will consume more meat and dairy products, which are more land-intensive than cereals. We show that about two-thirds of the increase in food prices can be attributed to changes in consumption patterns, and only a third from clean energy mandates.

Keywords: Clean Energy, Food Consumption, Land Quality, Renewable Fuel Standards, Transportation

JEL Codes: Q24, Q32, Q42

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1. Introduction

According to a recent issue of The Economist (2010), "by 2050 world grain output will have to rise by half and meat production must double to meet demand. And that cannot easily happen because growth in grain yields is flattening out, and there is little extra farmland…." These problems of yield stagnation and land scarcity are further exacerbated by clean energy policies that promote biofuels such as ethanol from corn and sugarcane. Many countries are actively promoting these renewable fuels to reduce greenhouse gas emissions and as a means of reducing dependence on foreign countries for vital energy supplies. Because of government subsidies, the production of plant-based fuels such as ethanol and biodiesel has grown sharply in recent years. For instance, about 10% of US gasoline now comes from corn ethanol.

The US Renewable Fuel Standard (RFS) mandates the minimum use of 36 billion gallons of ethanol by 2022. About 11 billion gallons are used at present. The European Union (EU) requires that biofuels must supply at least 10% of transportation fuels by 2020, from a current share of about 3%.

Several important issues have arisen with the increased production of biofuels. First, they use scarce land resources. Growth in biofuel production may well result in a large-scale shift in acreage from food to fuel leading to a reduction in food supplies and increased food prices.[2] By converting existing grasslands and forests into farmland, especially in developing countries which have a lower cost of production and can therefore compete successfully in a global biofuels market, there may be significant leakage of sequestered carbon into the atmosphere. Deforestation-induced carbon emissions may undermine the central argument for biofuels - that they are a low-carbon alternative to fossil fuels (Fargione *et al*. 2008, Searchinger *et al*. 2008).

In this paper, we examine the effects of biofuel mandates in the US and EU on world food prices. We develop a dynamic model of transportation and food demand with several unique features not considered previously in the literature. In our model, consumer preference for food is driven by

[2] A recent study by the International Food Policy Research Institute (Rosegrant *et al*., 2008) suggests that an aggressive expansion into biofuels will raise the price of certain food commodities by up to 70% by the year 2020.

per capita income levels, so that rising incomes (as in countries like China and India) imply a bias towards meat products which are more land-consuming than a diet based primarily on cereals. Per capita consumption of meat and dairy products in the developed world is about four times that in developing countries. For example, the disparity in meat consumption in the United States and China can be seen in Fig.1. As incomes in China rise, the gap in meat and dairy consumption is expected to narrow. This is important because eight kilos of cereals produce one kilo of beef and three kilos produce one kg of pork. Income-induced changes in dietary preferences have been largely overlooked in previous studies. We show that the projected future rise in food prices has a lot to do with the increased demand for meat and dairy products. Energy mandates play a relatively minor role.

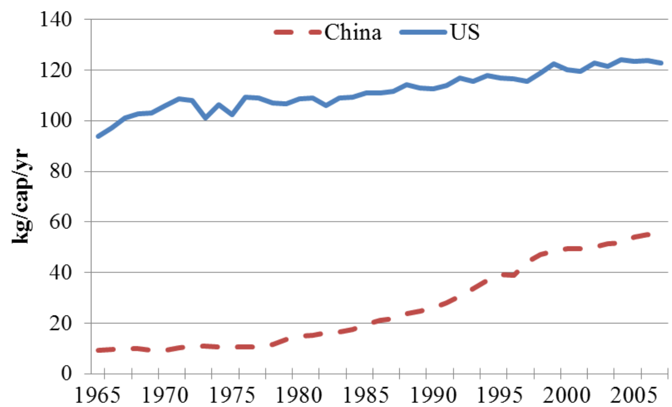


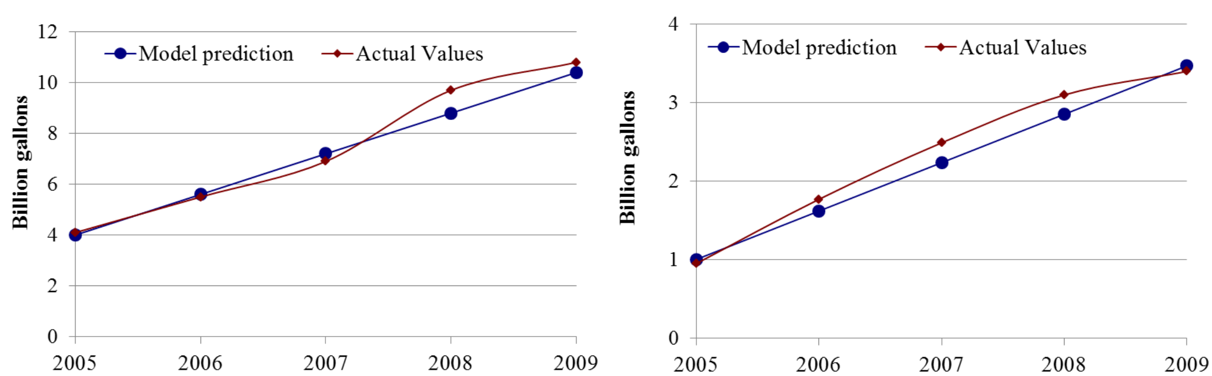
Figure 1. Meat consumption in China and US from 1965 to 2007
Source: FAOSTAT

We have endogenous land allocation in our model, so that rising food prices result in land conversion, especially in the developing countries, where most new land is located. There is significant heterogeneity in global land quality and most available land is of medium to low quality. By recognizing different land qualities, we can trace the effect of energy mandates in shifting production to lower quality lands and determine which regions will take up the slack in food and energy production. This also helps us estimate the resulting increase in carbon emissions.[3]

[3] Emissions from land conversion in our model depend on current use, e.g., cutting down forests for cropping emits almost twice the amount of carbon than farming pasture lands.

Finally, since gasoline and biofuel are substitutes, we take into account the rising cost of oil due to scarcity. As we show later in the paper, oil prices have a significant effect on the adoption of biofuels because they are substitutes in transportation.

The model was calibrated for the base year 2005. Since renewable fuel mandates have only been in existence since that year, it is not possible to test model predictions over a long time horizon. However, as shown in Fig.2, the model does track the boom in biofuel use in the US and EU quite closely until the most recent year for which data is available (2009). The difference between observed and projected values is systematically less than 10%. The model also predicts the annual increase in food prices from 2005 to 2009 at about 5%.[4] According to the FAO, food prices grew at an annual rate of 4% during this period.



(a) US biofuel consumption

(b) EU biofuel consumption

Figure 2. Model Prediction vs Actual Biofuel Consumption
Source: US (EIA 2010); EU (EurObserv'er 2007-10).

We use the model to first examine the counterfactual - a model with no mandates - to see how expected increases in population and incomes will affect demand for food and competition for land. The key insight is that because of increased demand for food due to population growth and income-induced shifts in dietary habits towards more meat consumption, food prices are expected to rise in the near future, even *without* energy mandates. Biofuel mandates which stipulate the use

[4] Our world food price is the average of cereal and meat prices weighted by the share of each commodity in total food consumption. In general, it is hard to accurately predict food prices in the short run, because of weather-related variability (droughts such as the one that occurred in Australia in 2008 or Russia in 2010), currency fluctuations and other macroeconomic phenomena.

of new technologies such as second generation fuels that use less land, have a muted effect on food prices.

However, the energy mandates have other effects. The US which is a major exporter of food to developing countries, experiences a large decline in food exports. US exports fall by about 70% by year 2025.This is because there is not much additional land available and existing farmland must be diverted to energy production.[5] This reduction in exports also occurs because subsidies and import tariffs prevent large-scale biofuel imports from lower cost developing countries. Reduced exports cause land conversion for food production in countries such as Brazil, Indonesia and Malaysia, which leads to an increase in indirect (i.e., from land-use changes, not direct production and use of biofuels) carbon emissions.

Mandates also cause a 'rebound effect," i.e., global oil prices fall due to reduced demand in the US and EU, leading to increased crude oil consumption by other nations that do not have energy mandates. Global emissions actually *increase*. Welfare declines in the developing countries.[6]

We consider how the model behaves when food preferences are assumed to be *insensitive* to income changes. The predicted rise in food prices (without the renewable mandates) falls by about a half, suggesting that the preference towards meat products does play a major role in causing food price increases and expansion of cropland. When the two emerging economies China and India impose domestic biofuel mandates, more land is brought under cultivation, leading to a doubling of indirect carbon emissions. Surprisingly, food price increases are limited even in that situation. They rise by an additional 2% compared to the US/EU mandate case.[7]

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[5] The United States accounts for 70% of world corn exports, 30-40% of the export market for wheat and soybeans and is a major exporter of many other crops.

[6] Mandates that prescribe the use of newer less land-intensive fuels such as second generation biofuels reduce the pressure on land, and have a muted effect on exports. These new fuels, which are less land-using, slow down the rise in food prices. However, they have a limited effect in curbing global emissions because they also reduce energy prices and lead to increased consumption of fossil fuels.

[7] Sensitivity analysis suggests that estimates of oil reserves have a significant impact on biofuel use. Lower oil stocks raise energy prices which induce increased biofuel production and land conversion in developing countries. Thus direct (due to combustion) emissions may go down, but indirect emissions increase. When oil prices are assumed to remain constant (at current levels), the result is higher direct emissions from fossil fuel burning but lower indirect emissions from less biofuel use and land conversion. Adoption of high yield crops such as GMOs (Genetically Modified Foods) increase yields and thus reduce pressure on scarce land.

A key implication of the paper is that in the long run, biofuel mandates affect aggregate food production marginally, even though they have a major impact on *where* the food is produced. Mandates imposed by the US and EU, and by other nations, will cause significant land conversion. We find that almost an area equal to current US farmland is brought under cultivation in the developing countries. This leads to significant emissions, defeating the original purpose of mandating biofuel use. Mandates also lead to lower oil prices and higher emissions due to leakage. Either way, they have almost no effect in reducing global greenhouse gas emissions, and increase it in some cases.

There are several important studies on the effect of biofuel policies but none explicitly considers changes in dietary preferences, heterogeneous land quality and energy scarcity. In general, most studies predict significant impacts of energy mandates on food prices. For example, Roberts and Schlenker (2010) use weather-induced yield shocks to estimate the supply and demand for calories and conclude that energy mandates may trigger a rise in world food prices by 20-30%.[8] Almirall, Aufhammer and Berck (2010) use structural vector auto-regression to examine the impact of biofuel production in the U.S. on corn prices. They conclude that one third of corn price increases from 2006 to 2008 (which rose by 28%) can be attributed to biofuels.[9]

Other studies have used the well-known trade and general equilibrium model (GTAP) to explore the impact of biofuels production on world agricultural markets, specifically focusing on US/EU mandatory blending and its effects on individual countries (Banse *et al.* 2008, Hertel *et al.* 2008a). In these papers, land quality is explicitly taken into account, but changes in food preferences and scarce energy supplies are not modeled. The static framework adopted does not allow for an analysis of long run impacts, as in our case.[10] Rosegrant *et al.* (2008) develop a partial equilibrium model of global agriculture in order to analyze the effects of biofuel mandates

[8] They acknowledge that "demand growth has accelerated through demand for meat and other animal-based foods, which are highly income elastic." However, they do not explicitly account for it in their estimation.
[9] Their short-run analysis may well be consistent with our prediction that in the long-run, the impacts may be significantly lower. This is because higher food prices are likely to trigger supply side responses only with a time lag, especially if significant land conversion were to occur.
[10] Schneider and McCarl (2003) focus on agriculture and adopt a partial equilibrium approach for land allocation between agriculture and forestry. Paltsev and Reilly (2009) build a detailed energy model where land quality is uniform across geographical areas. They ignore dynamic effects.

on specific crops. They assume a fixed amount of land and find a more pronounced increase in agricultural prices than in our study where land supply is endogenous.

How do we reconcile the above findings of large increases in food prices with our results? The answer may be that sustained increases in food prices will cause supply adjustments, mainly in the form of new land conversion. Static models or those that treat land endowments as fixed, are unable to address this issue. Moreover, in terms of effects on food prices, changing dietary habits may play a bigger role than diverting food for energy supplies, an issue not recognized in many of the earlier models. Finally, the US mandate places a major emphasis on second generation technologies, which are less land-using. As energy prices rise, they become economical and take a significant share of the biofuel supply. This dampens the effect on prices.

Section 2 describes the basic model structure and assumptions. Section 3 reports the results of the calibration. In section 4 we perform sensitivity analysis. Section 5 concludes the paper. The Appendix provides the data and parameters used in the model.

2. The Model with Heterogeneous Land Quality

In this section we discuss the model structure, while relegating some technical details and data to the Appendix. We divide the world into three regions using data on gross national income per capita (World Bank 2010a). These are High, Medium and Low Income Countries (HICs, MICs and LICs). Since our study focuses specifically on US and EU mandatory blending policies, the HICs are further divided into three groups - the US, EU and Other HICs. The five regions are indexed by $n = \{US,\ EU, Other\ HICs, MICs, LICs\}$ where n denotes region.

Table 1 shows average per capita income by region. The MICs consist of fast growing economies such as China and India that are likely to account for a significant share of future world energy demand as well as large biofuel producers like Brazil, Indonesia and Malaysia. The LICs are mainly nations from Africa.

We consider three final consumption goods - namely cereals, meat and dairy products and energy for transportation. Cereals include all grains, starch crops, sugar and sweeteners and oil crops.

Table 1. Classification of regions by income (US$)

Regions	Mean annual gross national income per capita in (2000-2005)	Major countries
US	42,040	-
EU	36,000	-
Other HICs	33,000	Canada, Japan
MICs	936 - 11,455	China, India, Brazil, Indonesia, Malaysia
LICs	below 935	Mostly African countries

Source: World Bank (2010a)

Meat and dairy products include all meat products and dairy such as milk and butter. For convenience, we call these two groups "cereals" and "meat." These goods compete for land that is already under farming as well as marginal lands, which are currently under grassland or forest cover. Obviously many other products can be included at a more disaggregated level but we want to keep the model tractable so that the effects of biofuel policy on land use are transparent. It is important to distinguish cereals from meat because their consumption is income-sensitive and the latter are more land intensive.[11]

Regional demands (for cereals, meat and transportation fuel) are modeled by means of Cobb-Douglas demand functions, which are functions of regional per capita income and population. Thus demand D_l for each final product l takes the form

$$D_l = A_l P_l^{\alpha_l} w^{\beta_l} N \tag{1}$$

where P_l is the output price of good l in dollars, α_l is the regional own-price elasticity, β_l is the income elasticity for good l which changes exogenously with per capita income reflecting changes in food preferences, w is regional per capita income, N is regional population and A_l is the constant demand parameter calibrated from data.

[11] On average, one hectare of land produces either one ton of meat or three tons of cereals and other crops (Bouwman 1997). There is a large disparity in meat consumption between developed and developing countries, which is expected to narrow over time as incomes converge. Per capita annual consumption of meat in the former is about 300 kg and only 70 kg in the developing world (FAO 2003). This translates to a per capita land requirement for food of 0.353 ha for OECD countries and 0.156 ha for LICs and MICs.

As incomes rise, we expect to observe increased per capita consumption of meat products relative to the consumption of cereals, as noted in numerous studies (e.g., Delgado *et al.* 1998, Keyzer *et al.* 2005).[12] We model the shift towards animal protein by letting income elasticities of food products decline with per capita income (as in Keyzer *et al.* 2005). Specifically, income elasticities for the US, EU and other HICs are taken to be stationary in the model since dietary preferences as well as income in these regions are not expected to change significantly in the long run. However, they will vary in the MICs and LICs due to the steep increase in per capita incomes. The higher the income, the lower is the income elasticity.[13] These elasticities are also specific to each food product (e.g., meat, cereals) as described in the Appendix.[14]

There are significant regional disparities in the growth of population which have implications for our model. While the population of high income nations (including the US and EU) is expected to be fairly stable over the next century, that of middle income countries is expected to rise by about 40% by 2050 and it is likely to double for lower income countries (United Nations Population Division 2004). Demand is also impacted by regional per capita income, which is assumed to increase steadily over time but at a decreasing rate, as in several studies (e.g., Nordhaus and Boyer 2000). Again, regional disparities are the norm, with the highest growth rates in MICs and LICs.[15]

Total available land area is the sum of current land under agriculture and marginal lands. The initial global endowment of agricultural land is 1.5 billion hectares (FAOSTAT).The regional distribution of land quality is not even, as is evident from Figure 3 which shows land endowments based on climate and soil characteristics. Most good land is located in higher income countries,

[12] In recent years, meat consumption has remained quite flat in the OECD countries (a total 8% growth during the period 1985-99). Cereal consumption has also been constant during this period (FAO 2003). However in the developing economies, meat consumption has grown sharply. While population doubled in China between 1961 and 2006, meat consumption grew 33-fold (Roberts and Schlenker, 2010). Since meat production is more land-intensive, this would imply a higher demand for land in food production.
[13] Appendix Table A3 reports the elasticity values used.
[14] It is important to recognize that not all developing countries have exhibited as large a growth in meat consumption as China. For example, a third of Indians are vegetarian and a change in their incomes may not lead to similar dietary effects. Moreover beef and pork are more land-intensive than chicken, the latter being more popular in countries like India. The distribution of income may also affect this behavior. If it is regressive, the effect on diets may be limited.
[15] Initial population levels and projections for future growth are taken from the United Nations Population Division (2004). Both world food and energy demands are expected to grow significantly until about 2050, especially in the MICs and LICs. By 2050, the current population of six billion people is predicted to reach nine billion. Beyond that time, population growth is expected to slow, with a net increase of one billion people between 2050 and 2100.

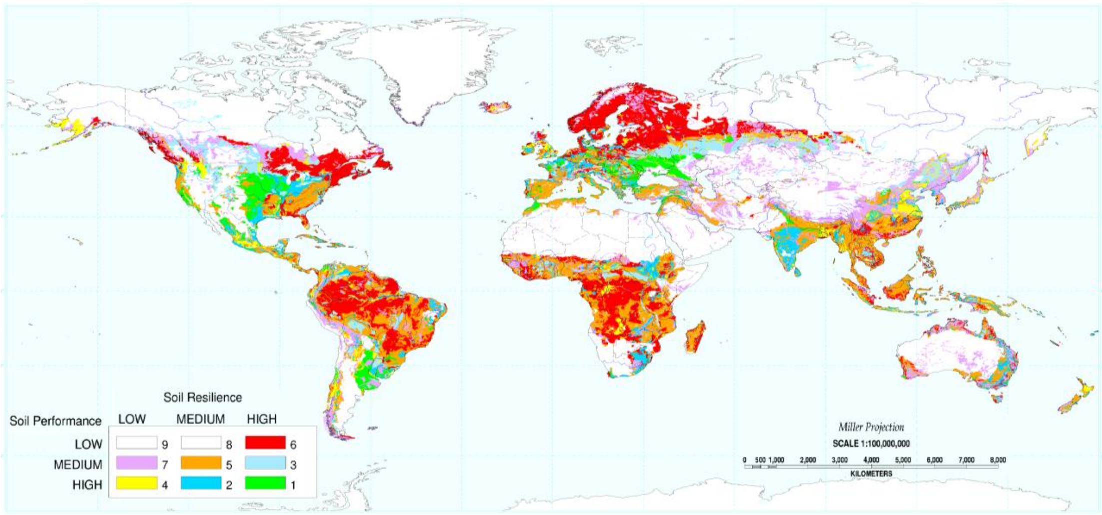

Figure 3. Distribution of land quality

Source: U.S. Department of Agriculture, (Eswaran *et al.* 2003 p.121). *Notes:* Land quality is defined along two dimensions: soil performance and soil resilience. Soil performance refers to the suitability of soil for agricultural production; soil resilience is the ability of land to recover from a state of degradation. Category 1 is the highest quality and 9 the lowest. In our model, we ignore category 7 through 9 which are unsuitable for agricultural production and aggregate the rest into three classes (categories 1 and 2 become class 1, 2 and 3 class 2 and 5 and 6 class 3).

but Brazil and India also have sizeable endowments of high quality land. There are three land classes in the model denoted by quality i, where $i = \{1,2,3\}$, with class 1 being the most productive land.[16] Initial acreage for each land class can be divided into cultivated lands ($\bar{L}_i$) and marginal lands (L_i^s). Cultivated lands may be allocated to different uses indexed by *j* which denote food crops, first and second generation biofuels. Land area can be increased by bringing marginal land under production. Cropping these lands implies increased carbon emissions.[17] They are mainly located in MICs and LICs.

More than half of the agricultural land in the HICs (US, EU and Others) is classified as land class 1, while the corresponding shares are only roughly a third for MICs and LICs, respectively, as shown in Table 2. Classes 2 and 3 are defined as marginal lands, which are essentially grasslands and forests, and located in MICs and LICs. Brazil alone has 25% of all marginal lands in the MICs and also happens to be the biggest producer of biofuels after the US. Note from Table 2

[16] See Appendix for more information on land classification.

[17] According to FAO (2008a), an additional 1.6 billion hectares of marginal lands could be brought under crop production in the future. This is approximately equal to the total land area already under cultivation.

Table 2. Land under Agriculture and Endowment of Marginal Lands

	Land class	US	EU	Other HICs	MICs	LICs	World
Land already under Agriculture (million ha)	1	100	100	25	300	150	675
	2	48	32	20	250	250	590
	3	30	11	20	243	44	350
Land available for farming (incl. marginal lands) (million ha)	1	0	0	0	0	0	0
	2	0	0	0	300	300	600
	3	0	0	0	500	500	1000

Sources: Eswaran *et al.* (2003), FAO (2008a).

that there are no Class 1 lands remaining for agricultural production. Future expansion must occur only on lower quality lands, namely classes 2 and 3.

Let $l_i^s(t)$ be the new land (cultivated or marginal) converted into agricultural use. We assume that the cost of bringing one hectare of marginal land into production is an increasing and convex function of the land converted in each region (as in Sohngen, Mendelsohn and Sedjo, 1999).[18] This is because access costs increase with land conversion. It is defined by

$$C_S(\sum_i l_i^S) = \phi_1 \left(\sum_i l_i^S \right)^{\phi_2} \quad (2)$$

where ϕ_1 and ϕ_2 are model parameters assumed to be the same across land class and region.

Food production is assumed to exhibit constant returns to scale for each land class in the model. Hence, regional food supply is just yield times the land area. Define yield of crop j on land class i as k_i^j. Then, total production of crop j from class i is $k_i^j L_i^j$.

Improvements in agricultural productivity are allowed to vary by region and land category (see Appendix). All regions exhibit increasing productivity over time, mainly because of the adoption of biotechnology (e.g., high-yielding crop varieties), irrigation and pest management. However,

[18] Their cost figures are for clearing forest land and preparing it for timber plantation, which should be a good approximation for conversion costs for farming. The data is available at http://aede.osu.edu/people/sohngen.1/

the rate of technical progress is higher in MICs and LICs because their current yields (conditional on land class) are low due to a lag in adopting modern farming practices (FAO 2008a). *Ceteris paribus*, the rate of technical progress is also likely to be lower for the lowest land quality. Biophysical limitations such as topography and climate reduce the efficiency of high-yielding technologies and tend to slow their adoption in low quality lands (Fischer *et al*. 2002).
The total cost of food or biofuel production in each region is assumed to be increasing and convex. The higher the production of food and biofuels, the more likely that cultivation moves into lower quality lands (van Kooten and Folmer 2004). Total production cost for product *j* in a given region is defined by

$$C_j(\sum_i k_i^j L_i^j) = \eta_1 \left[\sum_i k_i^j L_i^j \right]^{\eta_2} \tag{3}$$

where $\sum_i k_i^j L_i^j$ is the aggregate output of product *j*, and η_1 and η_2 are regional cost parameters.

Energy in the model is provided by oil as well as biofuels that are land using (often called First Generation biofuels) and newer technologies that are less land-using (Second Generation).[19] The latter aims to convert parts of the plant other than the fruit or grain into fuels.[20] They currently cost an order of magnitude more than first gen biofuels. Unlike the EU mandate which does not specify the precise biofuel, US regulation imposes a minimum amount of second generation biofuel use by 2022.

Since 95% of global transportation fuel is provided by crude oil which is a nonrenewable resource, it is reasonable to use a Hotelling framework to model energy supply.[21] Transportation energy q_e is produced from gasoline and biofuels in a convex linear combination using a CES specification, as in Ando *et al.* (2010) given by

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[19] We transform crude oil into gasoline using a coefficient of transformation equal to 0.3, taken from Chakravorty *et al.* (2010). Thus gasoline is a fixed share of oil. Since other uses of oil are not explicitly considered, the terms "oil" and "gasoline" are often used interchangeably in the paper where convenient.
[20] Examples include cellulosic material and crop residues.
[21] Later we check the sensitivity of the results to reduced oil reserves and when crude oil prices are constant over time (i.e., abundant oil at constant unit cost).

$$q_e = \lambda \left[\mu_g q_g^{\frac{\rho-1}{\rho}} + (1-\mu_g)(q_{bf} + q_{bs})^{\frac{\rho-1}{\rho}} \right]^{\frac{\rho}{\rho-1}} \tag{4}$$

where λ is a constant, μ_g the share of gasoline in transportation energy, ρ the elasticity of substitution, and q_g, q_{bf} and q_{bs} are the respective input demands for gasoline, first gen (generation) and second gen biofuels. The parameters λ and μ_g are calibrated from observed data. As the relative price of gasoline increases, the fuel composition switches towards using less of it.[22] The elasticity of substitution is region-specific and depends upon the technological barriers for displacing gasoline by first gen fuels in each region. It is higher in the HICs and lowest in the LICs. We use estimates made by Hertel et al. (2008a). As in many other studies, first and second gen biofuels are treated as perfect substitutes.

We define an exogenous world stock of oil and a single integrated “bathtub” world oil market as in Nordhaus (2009). At higher oil prices, new sources such as shale oil reserves become competitive. The stock of oil includes both crude and shale oil stocks. Estimated oil reserves in 2007 serve as the initial stock of oil, which amounts to 179 trillion gallons or 4.26 trillion barrels (WEC 2007). The unit cost of oil depends on the cumulative quantity of oil extracted (as in Nordhaus and Boyer 2000) and can be written as

$$C_{oil}(x(\theta)) = \varphi_1 + \varphi_2 \left(\frac{\sum_{t=0}^{\theta} x(t)}{\bar{X}} \right)^{\varphi_3} \tag{5}$$

where $x(\theta)$ is oil used in period θ, $\sum_{t=0}^{\theta} x(t)$ is cumulative oil extracted and $\bar{X}$ is the initial stock of crude oil.

[22] This specification captures the fact that there is still a large technological potential for displacing fossil fuels in passenger transport through blended gasolines such as E85 (85:15 biofuel:gasoline ratio), according to the OECD (2008).

Instead of allowing for the production of different types of first gen fuels in each region, we simplify consider a representative biofuel for each region. This assumption is reasonable because there is only one type of biofuel that dominates in each region. For example, 94% of production in the US is ethanol from corn, while 76% of EU production is biodiesel from rapeseed. Brazil, the largest ethanol producer among MICs, uses sugarcane. Hence, sugarcane is used as the representative crop for MICs. In the LICs, 90% of biofuels are produced from cassava, although it amounts to less than 1% of global production.[23] Table 3 shows the representative crop for each region and its production cost. These costs are assumed to decline by 2% a year (Hamelinck and Fajj 2006) mainly due to a decrease in processing costs.[24] Note the significant difference in costs across crops.

Table 3. Unit costs of first generation biofuels

	US	**EU**	**Other HICs**	**MICs**	**LICs**
Representative crop	Corn (94%)	Rapeseed[1] (76%)	Corn (96%)	Sugar-cane (84%)	Cassava (99%)
Unit cost of production ($/gallon)	1.01	0.55	1.10	0.57	1.30

Sources: Production costs (FAO 2008a; Eisentraut 2010); *Notes*: The numbers in parentheses represent the percentage of first-generation biofuels produced from the representative crop (e.g., corn).

We model a US tax credit of 46 cents/gallon, which consists of both state and federal credits (de Gorter and Just 2010). EU states have tax credits on biodiesel ranging from 41-81 cents (Kojima *et al.* 2007). We include an average tax credit of 60 cents for the EU as a whole.

Second gen biofuels can be divided into three categories depending on the fuel source: crops, agricultural and non-agricultural residue. They currently account for only about 0.1% of total biofuel production. More research is needed to reduce production costs as well as improve fuel performance and reliability of the conversion process. Compared to first gen fuels, they emit less greenhouse gases and are less land consuming.

[23] Reliable data on African production is difficult to obtain. Biofuel production in Africa is negligible in the model, mainly because there is no domestic demand for biofuels and land quality is low.
[24] Except for cassava, for which we have no data.

Since there are several second gen biofuels, we only consider the one that has the highest potential to be commercially viable in the near future, namely cellulosic ethanol in the US and biomass-to-liquid (BTL) fuel in EU (IEA 2009b).[25] Their energy yields are much higher than for first-gen biofuels. In the US, 800 gallons of ethanol (first gen) are obtained by cultivating one hectare of corn, while 2,000 gallons of ethanol (second gen) can be produced from ligno-cellulosic (Khanna 2008). In EU, around 1,000 gallons/ha can be obtained from BTL, but only 400 gallons/ha are obtained from first gen biofuels.[26]

Of course, second gen fuels are also more costly to produce. The full production cost of cellulosic ethanol is $3.5 per gallon while first gen corn ethanol currently costs about $1.01 per gallon and ethanol from sugar cane costs $0.57. The production cost of BTL diesel is $4.5 per gallon - twice that of first gen biodiesel. However, technological progress is expected to gradually narrow these cost differentials and experts predict that by 2030 or so, the per gallon production costs of second gen biofuels and BTL diesel are projected to be $2.08 and $2.27, respectively.[27] Finally, second gen fuels enjoy a subsidy of $1.01 per gallon in the US (Tyner 2009), which is also accounted for in the model.

The US mandate (Energy Independence Security Act, 2007) sets the US target for biofuels at 9 billion gallons annually by 2008, increasing to 36 billion gallons by 2022.[28] The bill specifies the use of first and second gen biofuels as shown in Figure 4. The former (corn ethanol) is mandated to increase steadily from the current annual level of 11 to 15 billion gallons by 2015. The bill requires an increase in the consumption of second gen biofuels from near zero currently to 21 billion gallons per year in 2022. In the EU the mandate (European Commission, 2008) requires a minimum share of biofuels of 10% in transportation fuel by 2020. Unlike the US, the EU has no regulation on the use of second gen fuels.

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[25] Cellulosic ethanol is a substitute for ethanol. It is produced from ligno-cellulosic (i.e., plant biomass) which is transformed into alcohol. Corn stover, switchgrass, miscanthus and woodchips are some examples. Since the whole plant is used, second gen biofuels are more energy efficient. Biomass-to-liquid fuels (BTL) are a substitute for biodiesel produced from biomass, such as short rotation trees, perennial grasses and straw.

[26] That is, when we say second generation biofuels, for the US it means cellulosic ethanol and for EU it implies BTL.

[27] All data on production costs are from IEA (2009b).

[28] It is not clear whether the mandates will be imposed beyond 2022 but in our model, we assume that they will be extended until 2050. In fact ethanol use in the US is close to hitting the 10% “blending wall” imposed by Clean Air regulations which must be relaxed for further increases in biofuel consumption.

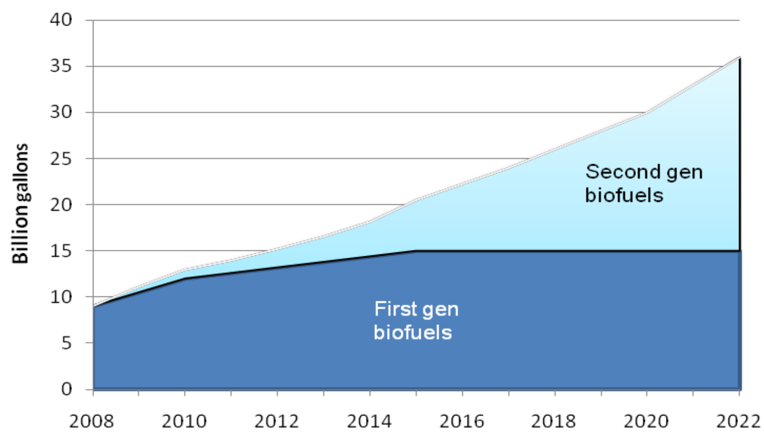


Figure 4. US biofuel mandate

The model accounts for both direct and indirect carbon emissions. It distinguishes between direct carbon emissions from fossil fuel consumption in transportation and indirect carbon emissions induced by the conversion of marginal lands into agriculture. Carbon from biofuel use is mainly emitted during production and hence is crop-specific. Considering only direct emissions, displacing gasoline by corn ethanol reduces emissions by 50%; 80% if displaced by sugarcane. Second-generation biofuels reduce carbon by 90% compared to gasoline. Any conversion of marginal lands (land class 2 or 3) for farming releases carbon into the atmosphere.[29] Using Searchinger *et al.* (2008), we assume that the carbon released is 300 and 500 tons of CO_2 per hectare respectively for land classes 2 and 3, immediately after land conversion. Carbon released from clearing pastureland is lower than for forests. Therefore, emissions are lower on class 2 land than on class 3 since the former has more pasture and the latter more forest.

Goods are treated as perfectly homogenous. We assume frictionless trading in crude oil and food commodities between countries. In reality, there are significant trade barriers in agriculture, but given the level of aggregation in our model, it is difficult to introduce tariffs, which are mostly commodity-specific (sugar, wheat, etc.). However, we do model US and EU ethanol tariffs. The US ethanol policy includes a per unit tariff of $0.54 per gallon and a 2.5% *ad valorem* tariff

[29] This is a gradual process. For forests it also depends on the final use of forest products. We assume that all carbon is released immediately following land-use change, an assumption also made in other well-known studies (e.g., Searchinger, *et al.* 2008).

(Yacobucci and Schnepf, 2007). The EU specifies a 6.5% *ad valorem* tariff on biofuel imports (Kojima *et al*. 2007).

We maximize the consumer plus producer surplus given regional demand functions for food and energy (denoted by subscript l) where energy may be supplied by gasoline, and first and second generation biofuels. Costs include the cost of production of food and energy from land (given by C_j), the cost of land conversion (C_s) and the cost of supplying oil (C_{oil}). The choice variables are the consumption of crude oil (x), land of quality i allocated to each use j (L_i^j) and marginal lands brought under cultivation (l_i^s). Endowments include the initial stock of crude oil and land of quality i. The maximization problem where we hide the time and region subscripts (respectively, t and n) can be written as[30]

$$\underset{x, L_i^j, l_i^s}{Max} \sum_{t=0}^{\infty} \left\{ \frac{1}{(1+r)^t} \left[\sum_n \left[\sum_l \int_0^q D_l^{-1} d\theta - \sum_j C_j (\sum_i k_i^j L_i^j) - C_s (\sum_i l_i^s) \right] - C_{oil}(x)x \right] \right\} . \qquad (6)$$

The relative prices of biofuels and gasoline determine their share in the total energy mix. Without the mandates, as energy demand increases over time and oil stocks deplete, the price of gasoline increases (at least over an initial time period) inducing substitution into biofuels. The energy mandates accelerate this substitution process. However, the demand for food also goes up because of population growth and changes in dietary preferences, and this limits the conversion of high quality land from food to energy production. The discount rate is assumed to be 2% as is standard in such analyses (Nordhaus and Boyer 2000). The model is simulated over 200 years (2005-2205) in steps of five, to keep the runs tractable.

3. Simulation Results

We first state the scenarios modeled in the paper and then describe the results. In the *Baseline case* (model BASE), we assume that there are no energy mandates and both first and second gen fuels are available. This case serves as the counterfactual. The idea is to see how substitution into biofuels takes place in the absence of any clean energy regulation. In the *Regulatory Scenario*

[30] The complete set of model equations is available from the authors.

(model REG), US/EU mandatory blending policies, as described earlier, are imposed.[31] We also run a *Flexible Mandate* scenario (model FLEXREG), in which both first and second gen biofuels can be used to meet mandatory blending specifications, but there is no requirement on the share of second gen fuels. This is mainly to examine how much of second generation biofuels (which are less land-intensive) will be produced if they are not explicitly mandated. The key results are as follows:

1. Limited Effect of Biofuel Mandates on Food Prices in the Long Run[32]

Perhaps the most significant finding is that the effect of renewable fuel standards (RFS) on food prices is actually quite modest, as in model REG (see Table 4). With no energy mandates, food prices rise by about 13%, which is purely from changes in population and consumption patterns (see model BASE).[33] With energy mandates, they go up by 18% (see REG). Thus the additional increase in 2025 from energy regulation is about 5%.[34]

Table 4. World food, biofuel and gasoline prices (in 2005 Dollars)

		BASE	**FLEXREG**	**REG**
Weighted food price ($/ton)	2010	**761**	869	771
	2025	**864(13%)**	**1133 (30%)**	**911(18%)**
Biofuel price ($/gallon)	2010	2.2	2.5	2.5
	2025	3.1	3.6	3.3
Crude oil price ($/barrel)	2010	79	78	78
	2025	121	119	119

Notes: Weighted food price is the average of cereal and meat prices weighted by the share of each commodity in total food consumption. The numbers in brackets represent the percentage change in prices between 2010-25. Our predictions for crude oil prices are quite close to US Department of Energy (EIA 2010 p 28) projections of $115/barrel in 2025.

[31] Recall that the US mandate stipulates an increase from 8 to 36 billion gallons a year by year 2022 which must include at least 21 billion gallons of second generation fuels. EU legislation only specifies a minimum share of biofuels in transportation of 10%.

[32] Our results are time sensitive but to streamline the discussion, we mostly focus on the year 2025. In the more distant future (say around 2050 and beyond), rising energy prices and a slowing down in demand growth makes biofuels economical, even without any supporting mandates. Mandates become somewhat redundant by then. Given the lack of space, we do not discuss what happens in 2050 and beyond.

[33] The model is calibrated to track real food prices in 2005. Cereal and meat prices for that year for the BASE case are $170 and $1,700 per ton. Observed prices in 2005 were $175 and $1,800 (World Bank 2010b).

[34] Since the model is dynamic, the initial conditions are endogenous, hence the starting prices in 2005 are not exactly equal (Table 4).

This is much smaller than what most other studies predict (Banse *et al.* 2008, Rosegrant *et al.* 2008, Roberts and Schlenker 2010).[35] Without mandates on second generation biofuels, food price increases are higher (about 30%), see model FLEXREG for the year 2025. Note that food prices decline ultimately towards 2050 as the effects of the mandates wear off. This is mainly because population growth levels off by that time horizon and output increases due to technology improvements in agriculture.

Figure 5 shows the time trend in food prices under the three regimes. Note that prices increase both with and without regulation.[36] The substantial increase in food demand in MICs and LICs

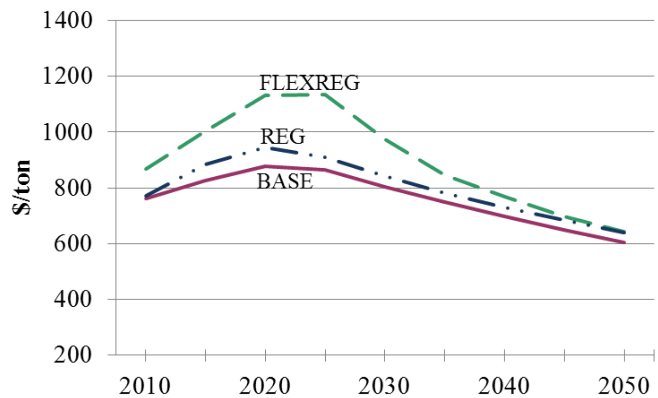


Figure 5. World weighted food prices

Notes: The baseline model is in red and the regulated models are the green and blue lines. The weighted food price is the average of cereal and meat prices weighted by the share of each commodity in total food consumption.

accompanied by a change in dietary preferences raises the demand for land, which drives up its opportunity cost. Meat consumption in these two regions in the model increases by 21% and 79% between 2010 and 2025, while the consumption of cereals remains stable. Since more land is used per kilogram of meat produced, the overall effect is increased pressure on land.

[35] In general, it is difficult to compare outcomes from different models, but Rosegrant et al. (2008) predict prices of specific crops such as oilseeds, maize and sugar rising by 10-25% in 2020 which is significantly higher than in our case. Roberts and Schlenker (2010) project that 5% of world caloric production would be used for ethanol production due to the U.S. mandate. As a result, world food prices in their model rise by 30%.

[36] Although real food prices have declined in the past four decades, the potential for both acreage expansion and intensification of agriculture through improved technologies is expected to be lower than in the past (Rosegrant *et al.* 2001). From 1960 to 2000, crop yields have more than doubled (FAO 2003). But over the next five decades, agricultural yields are expected to increase by only about 50%, see the data presented in the Appendix (Table A6). However, yields may also respond to higher food prices, an effect we do not capture here. Although that will imply an even smaller impact of energy mandates on food prices.

Although a 5% increase in food prices may seem small, it may still have major impacts on consumption by the poor and food security in lower income nations where a relatively high share of income is spent on food.[37] The impacts are regressive, with richer regions impacted less and the poorest regions hit the hardest. LICs exhibit higher price elasticities and are therefore more sensitive to increased food prices. For example, US per capita food consumption in 2025 declines due to mandatory blending (REG) by about 2% and 0.6% for meat and non-meat foods, respectively. The same numbers are much higher for MICs - nearly 11% and 4%.

2. *US food exports reduce sharply: Developing countries must now grow more of their own food, thus inducing conversion of marginal lands*

With regulation, global food production goes down and food prices increase. Food production in the US/EU declines but rises in the MICs. These countries must now produce more food and bring new land under cultivation (Table 5). MICs bring 24 (=967-943) million additional hectares

Table 5. Land allocation to food and energy production (in million ha)

		US		EU		MICs	
		BASE	**REG**	**BASE**	**REG**	**BASE**	**REG**
Land under food production	2010	166	166	137	137	786	786
	2025	151	110	132	127	933	958
Land under biofuel production	2010	12	12	6	6	7	7
	2025	27	68	11	16	10	9
Total cultivated land	2010	178	178	143	143	**793**	793
	2025	178	178	143	143	**943**	**967**

Notes: Land allocation in Other HICs and LICs are similar across the different scenarios.

under cultivation. However the table shows that the really big increases in land use occur even without these mandates: in the MICs, 150 million ha (=943-793) are brought under production between 2010-25 without any mandates (see BASE). Most of this additional land is located in three MIC nations – Brazil, Indonesia and Malaysia. The new land brought under farming is almost equal to the entire current acreage in US agriculture.

[37] This is an issue that needs to be considered in future research and may be relevant for countries like India which have large numbers of people living below the poverty line.

Both first and second gen biofuel production increases sharply under the US mandate (see Table 6). US food production declines by almost 25% as a result of the energy mandates (not shown). US food exports go down by more than 70% (61 to 17 million gallons). This is because land is shifted out of food to produce biofuels for domestic consumption. Imports of first gen biofuels increase almost three fold, even with the import tariff in place (see Fig.6).

Table 6. Biofuel production (billion gallons)

	Year	US		EU		MICS	
		BASE	REG	BASE	REG	BASE	REG
Total biofuels	2010	8.1	10.7	3.3	4.3	8.1	8.1
	2025	**13.7**	**35.1**	**3.0**	7.5	12.3	11.4
First gen biofuels	2010	8.1	**10.7**	3.3	4.3	8.1	8.1
	2025	7.2	**14.1**	3.0	3.6	12.3	11.4
Second gen biofuels	2010	0	**0**	0	0	0	0
	2025	6.5	**21.0**	0	3.9	0	0

Notes: Our numbers are calibrated to observed data. In 2010, average US biofuel production was 10.6 billion gallons, 4 billion in the EU and 8 billion in MICs. Second gen fuel supply was negligible.

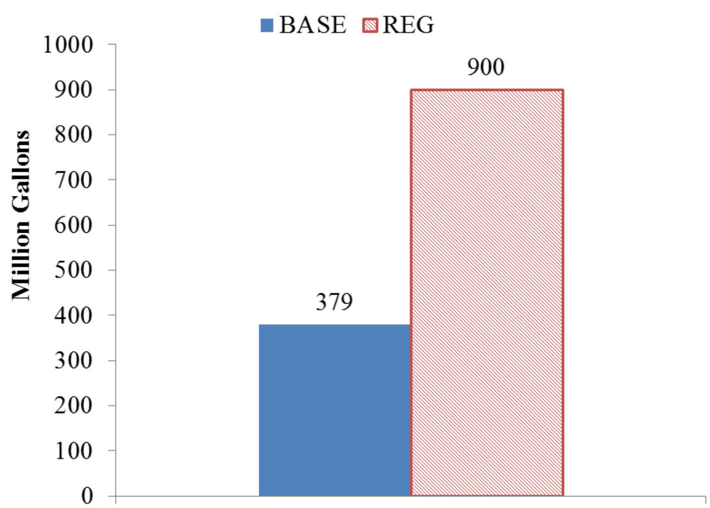


Figure 6. US biofuel imports with and without energy mandate

Fig.7 shows land use in food and energy.[38] Note that in the US about 41 million ha are moved from food to fuel production. But no new land is added. This is plausible because there is really

[38] We don't show the EU case because it does not change appreciably.

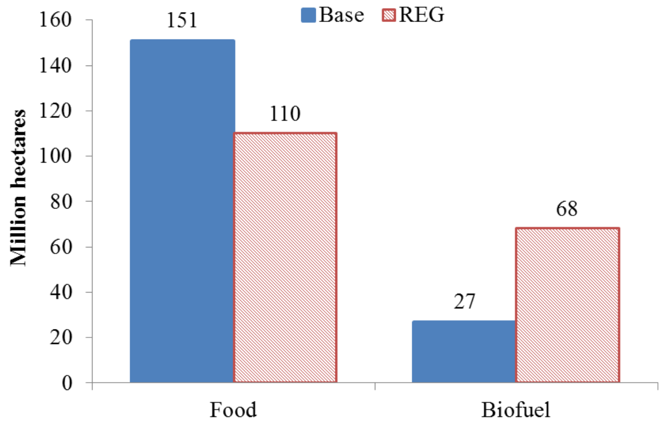


Fig. 7(a). Land allocation in US: land is shifted out from food to fuel

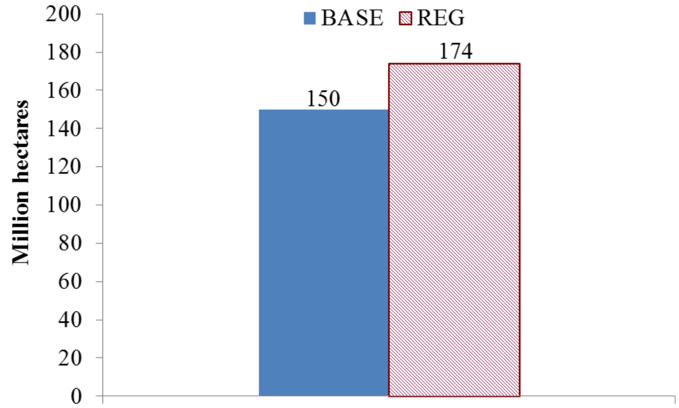


Fig. 7(b) Land Conversion in MICs

Figure 7. Land allocation under Base and REG (year 2025)

Notes: An area equal to entire US farmland is cleared in the MICs

not much new land that can be brought under cultivation. However, the MICs convert a significant amount of land, irrespective of the energy mandates.

3. Second generation biofuels have a significant impact in terms of reducing land scarcity and limiting the increase in food prices

The role of second gen biofuels can be seen by comparing the results under FLEXREG which allows for the composition of first and second gen fuels to be determined endogenously and REG, which prescribes a minimum share of the latter (see Table 7). With regulation, second gen biofuel production nearly doubles from 11.4 to 21 billion gallons. Production of first gen fuels declines in the US and import of biofuels also falls. Aggregate food production declines by about 7%, which is somewhat surprising. One may intuitively expect more food to be produced when newer less

Table 7. Effects of US second generation mandates on biofuel and food production (in 2025)

		First gen biofuel production	Second gen biofuel production	Net export biofuel	Food production
		billion gallons		million gallons	million tons
US	REG	14.1	**21.0**	-900	**411**
	FLEXREG	23.4	**11.4**	-1,232	**444**
MICs	REG	11.4	0	2,189	2,029
	FLEXREG	11.9	0	2,501	2,000

Note: We only report the regions impacted most by second gen biofuel regulation. The numbers do not change significantly for the EU.

land-using biofuels are mandated. However, US food exports double under second gen fuels, albeit from a low base. Food is still produced in mostly high quality lands. The combined effect of an increase in food exports and decrease in biofuel imports limits the conversion of marginal lands overseas. In summary, regulation of second gen biofuels helps reduce imports, but does not release land for more food production. Biofuel prices fall by about 8% in this case.

4. *Mandates lead to big increases in biofuel production, earlier in time*

Without regulation, biofuel consumption in the EU and US in 2025 is three and 14 billion gallons, and accounts for 4% and 8% of fuel consumption, respectively. This is much lower than what is prescribed by the mandates. Figure 8 shows consumption with and without the mandates (BASE, REG). The mandatory blending policy requires an additional 26 billion gallons of biofuels in 2025 compared to the unregulated case, mostly in the US.[39] In the EU, the mandate is binding until 2030 (see panel c). The US target is much more ambitious. It binds until 2050 (see panels a and b). The gap in consumption with and without the mandate is bigger in the US than in the EU.

As seen from Fig. 8(a) and 8(c), first gen fuels decline in use without a mandate for several years before becoming economical in response to rising energy prices. After 2025, the use of first gen biofuels increases even without a mandate. In the absence of regulation, the global share of oil in transport steadily decreases from 95% in 2010 to 88% in 2050. The share of biofuels increases, mainly due to a considerable increase in the market share of second gen fuels. Even with no

[39] Global biofuels production under the baseline scenario is 29 billion gallons in 2025.

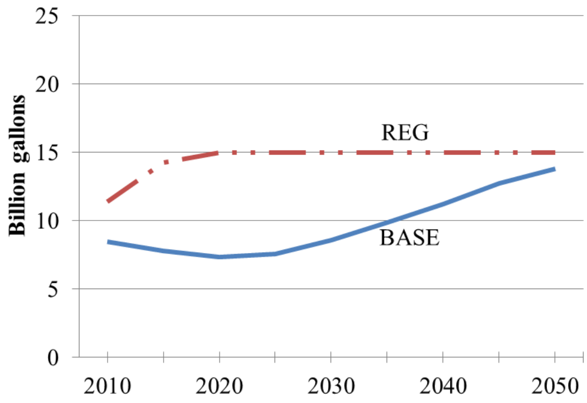


Fig. 8(a) US First Gen biofuel use

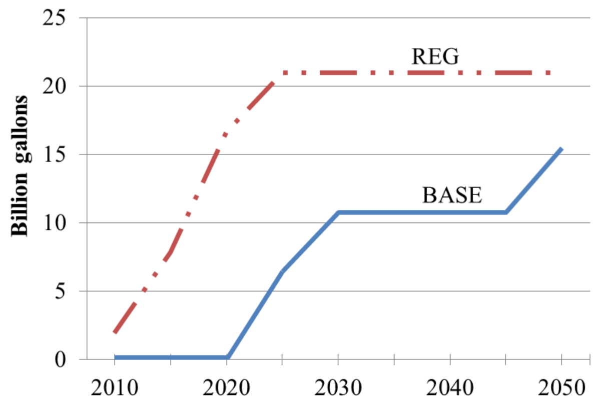


Fig. 8(b) US Second Gen biofuel use

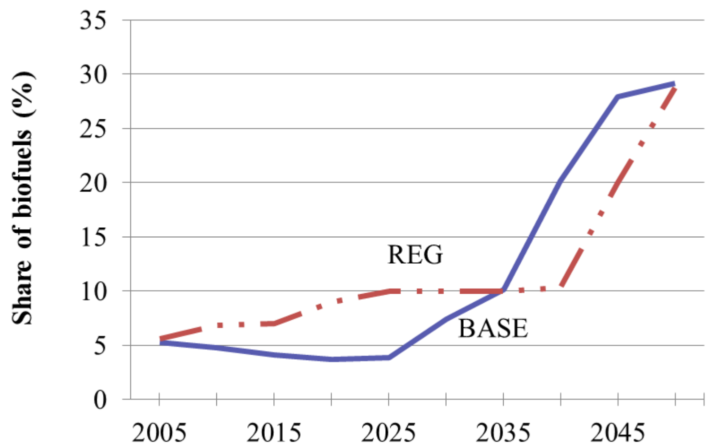


Fig. 8(c) Share of biofuel in transport in EU

Figure 8. US and EU biofuel use (with and without mandates)

Notes: The US mandate is more stringent, as can be observed by the vertical distance between the dashed and solid lines. Since the EU mandate is in percent terms, we report percent figures for it.

regulation, they are economically viable in the US by 2025. By 2050, they account for about 5% of global transportation energy. The production of first gen fuels, however, does not show nearly the same rapid growth, in spite of regulation, mainly because of competing demands for land (see Fig. 8a and 8c).

With no regulation, annual world production of biofuels is constant at about 20 billion gallons until 2020, increasing to 54 billion in 2050 (not shown). The stagnation until 2020 is due to a rapid increase in the opportunity cost of land, caused by the growing demand for food. Indeed, land rents double in the US and EU during this period. Beyond 2020 however, food demand levels off, and so do land rents. However, the scarcity rent of oil continues to increase, making gasoline expensive and biofuels economically feasible (see Fig.8).

5. Mandates reduce global oil prices and causes major terms of trade effects

The primary goal of biofuel regulation is to reduce direct emissions from the energy sector. US emissions fall by 9% while those of the EU by about 6% in 2025 (see Table 8).

Table 8. Direct carbon emissions in billion tons of CO_2 (REG)

	US	**EU**	**World**
2010	2.5	1.1	6.7
2025	**2.6 (-9%)**	**1.1 (-6%)**	**8.5 (-1%)**

Note: Numbers in parenthesis represent the percentage change of carbon emissions compared to BASE model, which is not shown here.[40]

The mandates, while increasing the consumption of biofuels in the US/EU, increase oil consumption and reduce biofuel use elsewhere. This occurs because of terms of trade effects - the increased demand for biofuels lowers the world price of oil (see Table 4). In 2025 the price of oil is about 2% lower, while the price of biofuels increases by 6% with mandatory blending. The net effect is that biofuel consumption outside the US and EU goes down by 10% in 2025, most of it in MIC countries. MIC oil consumption goes up by 2%.

Annual direct emissions of carbon increase by about 6% in the rest of the world.[41] Although the US/EU consume a significant share of global transportation energy - 56% in 2010 which declines to 35% in 2050 - the reduced emissions in these regions are not enough to offset the carbon leakage in other regions. Hence, the net effect of mandatory blending policies on global direct emissions is small (Table 8).

In the BASE model, direct emissions from US/EU and other high income countries are expected to be relatively constant over time since energy use is approximately constant (the rate of substitution between gasoline and biofuels is small), while the emissions of other regions show

[40] Observed average carbon emissions for previous years are close to our model predictions: they equal 2.2, 1.1 and 6.7 tons of CO2 for the US, EU and World in 2008 (IEA, 2010).

[41] Direct emissions from the rest of the world go up from 4.4 billion tons of CO_2 in BASE to 4.6 billion tons in REG in 2025.

steady growth because of increases in income and population. The majority of the growth in carbon emissions will occur in MICs. Considering only direct carbon emissions, medium income countries (mainly led by China and India) surpass high income nations and as a group become the largest carbon emitter by 2040. This is because consumption of fuel for transportation in MICs exceeds that in the US and EU combined. The results also predict considerable growth in low income regions, but starting from a much smaller base.[42]

6. Indirect carbon emissions increase

Biofuel mandates lead to an *increase* in indirect global emissions (see Fig. 9). The mandates increase total emissions in most years relative to the unregulated (BASE) case, which to a large degree is due to land conversion. Total emissions (direct and indirect) also increase in the near term (see Figure 9).

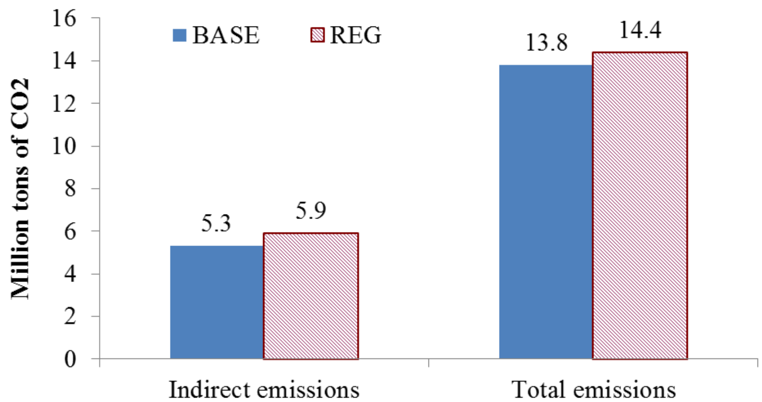


Figure 9. Biofuel Mandates do not Reduce Carbon Emissions

Notes: Total emissions are the sum of direct and indirect emissions.

Carbon emissions from land-use changes account for about 20% of global greenhouse gas emissions, making it the second largest source of emissions after the electricity sector (WRI 2010). Since most indirect carbon emissions are released through the production of first gen biofuels and food, we can compute them from the model. Regardless of whether biofuels mandates are imposed, the increased demand for food causes large-scale land conversion. However, the mandates only accelerate this process, especially for the middle income countries. In 2025, indirect carbon emissions increase by 10% (or 0.6 billion tons of CO_2). By adding direct

[42] These results are not shown here because of space constraints.

and indirect carbon emissions, we immediately see that total carbon emissions increase by about 0.5 billion tons of CO_2 due to mandatory blending (see Fig. 9).

7. Welfare declines in other countries

We can compute the regional gains and losses in aggregate consumer and producer surplus as a result of the mandates (Figure 10). Medium income countries experience the largest loss in welfare with mandatory blending, followed by low income nations. This welfare loss (for MICs) amounts to almost half a trillion dollars annually and increases rapidly until 2020 before

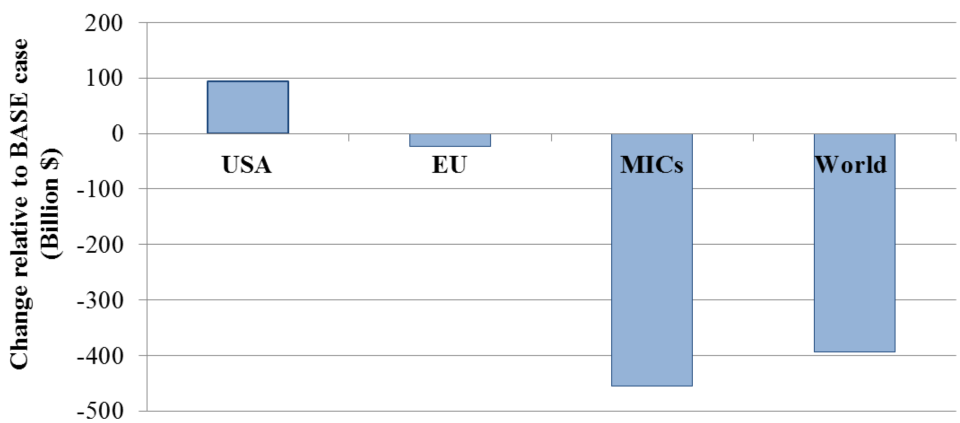


Figure 10. Welfare impacts of US and EU mandates relative to No Mandate

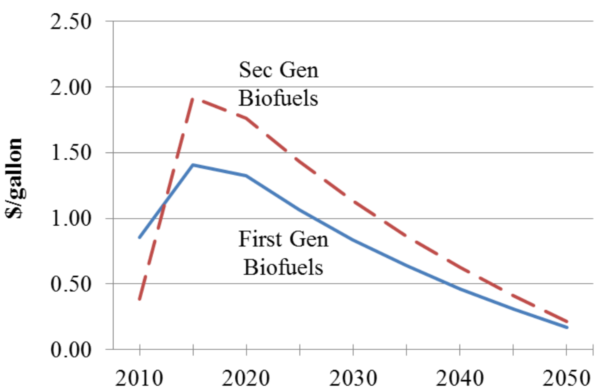
Note: Biofuel mandates impact the welfare of MICs and LICs the most. The US shows a small improvement in welfare relative to the unregulated scenario.

declining. EU also experiences a loss in welfare under the mandates compared to the unregulated case, but by a smaller degree because consumers in the EU are less sensitive to a rise in food prices. However, the US experiences a slight *increase* in welfare. These results are primarily driven by changes in surplus from agriculture. The mandates increase biofuel production, which causes an increase in the opportunity cost of land, which in turn drives up the price of agricultural products (both food and energy). This has a significant positive impact on surplus in the US agricultural sector, which is one of the objectives of the US mandate (de Gorter and Just 2010).

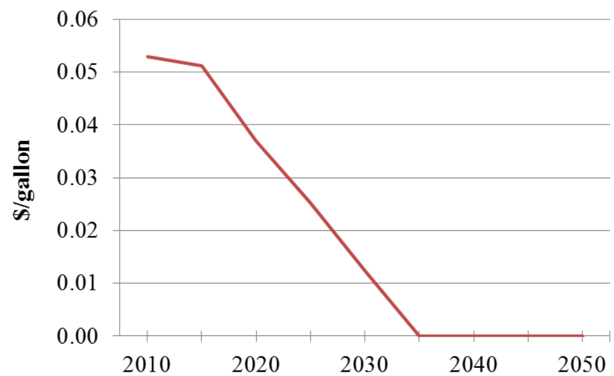
The global welfare effects of introducing mandatory blending is clearly negative. In the MICs and LICs - countries where a large share of income is allocated to food consumption, consumers are more sensitive to changes in food prices. As a result, the loss in welfare of food consumers exceeds the gain to food producers (from higher food prices). Note however, that we do not include the benefits from reduced carbon emissions in the mandated nations, and given that greenhouse gases are global pollutants, it is not clear whether any benefits accrue to the countries imposing mandates. On the other hand, higher emissions in other nations due to terms of trade effects will cause environmental damages that will likely reduce aggregate welfare.

8. The US mandate is stricter than that of the EU

The associated shadow prices of the mandates yield the subsidy needed to meet biofuel targets in the regulated countries.[43] The subsidy is only positive when the policy constraint is binding (see Figure 11). The US subsidy is an order of magnitude higher than in the EU. The subsidy required to meet the second gen requirement is higher than the first gen subsidy, which can be explained by the relatively high production cost of second gen biofuel technologies still in their infancy. Prior to 2015, the requirement on second gen biofuel consumption is relatively small and therefore less costly to impose.[44]



(a) US subsidy for first and second gen Biofuels



(b) EU subsidy

Figure 11. Implicit biofuel subsidies: US subsidies are much larger than in EU

Notes: Since the EU mandate does not differentiate between first and sec gen use, the subsidy is given to all biofuels.

4. Model Sensitivity to Parameter Values

There is uncertainty regarding the values of several key parameters used in the empirical analysis.

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[43] This subsidy would be in addition to the current tax credits described earlier in the paper.

[44] Ando *et al.* (2010) report per gallon subsidies of $1.67 for corn ethanol and $2.23 for cellulosic ethanol for 2015, similar to our figures (respectively, $1.40 and $1.95).

These include the stock of oil and its cost of extraction, the conversion cost of marginal lands, the production cost for second gen biofuels and yield parameters for crops. In this section we investigate the sensitivity of our results to changes in these parameters. In addition, we analyze the implications of lifting the current trade restrictions in the US and EU.[45]

Our strategy is to study the model with full regulation (model REG) with the following changes: (1) a 20% lower initial stock of oil (2) 50% lower conversion cost for marginal lands (3) no trade restrictions on biofuels (free trade) (4) reduction in the initial cost of second gen biofuels and (5) a 15% increase in agricultural yields because of adoption of biotechnology.[46] We also examine the effect of regulation by major countries such as China and India.

There is considerable uncertainty concerning the production costs of second gen biofuels. IEA (2009b) has developed a set of cost projections based on the potential market penetration of second gen biofuels where the cost and its rate of decline over time depend on crop prices, economies of scale from large plants, integration of new technologies and the effects of experience and learning. For production costs in the benchmark models we have used their conservative estimates. In the sensitivity analysis we apply their optimistic projections which yield costs that are lower by about 15% for both the US and EU. We model the adoption of genetically modified foods that may raise agricultural yields through introduction of new cropping varieties that are plant and disease resistant and do well in arid environments (OECD 2009).[47] Biotechnologies are currently adopted by the world's largest agricultural producers except the EU and occupy about 10% of global crop area.[48] We assume a reasonable across-the-board increase in agricultural yields of 15% relative to the models described earlier.[49] To keep it

[45] Because of a lack of space, we are unable to show all our sensitivity results. We discuss only the most significant ones.

[46] An increase in the cost of extraction of oil is not considered, but would have a similar effect as a reduction in the initial stock of oil since both would raise energy prices. Preliminary runs suggest that the model is not very sensitive to an increase in the cost of extraction of oil.

[47] The adoption of Genetically Modified Organisms (GMOs) can help biofuel production by increasing the production of biomass per unit of land as well as the conversion of biomass to first or second gen biofuels (FAO 2008b).

[48] The US leads in the adoption of biotechnologies, followed by Brazil, Argentina and to a lesser extent India and China.

[49] According to the Council of Biotechnology Information (2008), adoption of GMOs contributed to a 15% increase in US crops yields during 2002-07. Due to a lack of data for other countries, we apply this rate of increase across the board.

simple, this increase in yields is assumed to be uniform across land classes and across regions. In addition, it equally affects food and both types of biofuels.

The results are summarized in Table 9 while the impact on carbon emissions is reported in Table 10. Lower oil reserves raise energy prices, which in turn lead to higher food prices since land is shifted out from food to energy production (Table 9). Lower oil use also reduces direct emissions (see Table 10). However, less oil use and higher oil prices induce more biofuel production, which

Table 9. Sensitivity analysis: Effect of changes in model parameters on the model with mandates (year 2025)

	REG	**Lower oil reserves**	**Lower land conversion cost**	**No biofuel trade barriers**	**Lower cost of second gen fuels**	**Higher adoption of biotech**
Food price (US$/ton)	911	951	880	896	**886**	**805**
Biofuel price ($/gal)	3.3	3.4	3.1	3.2	3.3	2.9
Gasoline price($/gal)	2.8	3.9	2.9	2.9	2.8	2.8
Net Exports						
US food (mil tons)	**17**	18	**32**	19	18	**42**
US biofuels (mil gal)	**-900**	-940	**-1,350**	**-2,160**	-1,048	-720
EU biofuels (mil gal)	-111	-131	-276	-473	-112	-95
Food production (million tons)						
US	411	412	413	416	412	459
MICs	2,000	1,965	2,050	2,026	2,060	2,128
Biofuel production (billion gallons)						
US	35.1	35.1	34.6	33.8	34.9	35.3
EU	7.5	18.1	7.4	7.3	7.5	7.8
MICs	**11.4**	**14.4**	12.7	13.1	11.8	**14.1**
First gen biofuel consumption (billion gallons)						
US	15.0	15.0	15.0	15.0	15.0	15.0
EU	3.7	2.8	3.7	3.7	3.7	4.0
MICs	9.2	9.7	8.9	7.8	9.4	9.4
Second gen biofuel consumption (billion gallons)						
US	21.0	21.0	21.0	21.0	21.0	21.0
EU	3.9	15.4	3.9	3.9	3.9	3.9
Aggregate acreage used (million hectares)						
World	**1,807**	1,815	1,845	**1,940**	**1,941**	1,777

Note: mil=millions, gal=gallons. The benchmark model REG is shown in the left hand column.

leads to more marginal lands being brought under cultivation. This increases indirect emissions, mainly in other countries (see Table 10).

Table 10. Sensitivity analysis: Impact of energy mandates on carbon emissions (year 2025, in billion tons of CO_2)

	REG	Lower oil reserves	Lower land conversion cost	No biofuel trade barriers	Lower cost of second gen fuels	Higher adoption of biotech
Direct emissions						
US	2.6	2.3	2.6	2.6	2.6	2.5
EU	1.1	0.7	1.1	1.1	1.1	1.2
World	8.5	7.0	7.9	8.5	8.5	8.5
Indirect Emissions	5.9	6.0	7.6	**11.8**	11.9	3.6
Total Global Emissions	**14.4**	12.3	15.5	**20.3**	**20.4**	12.2

A reduction in the conversion cost of new land leads to more marginal land being converted for agricultural production in the MICs, which have surplus land endowments. First gen biofuels from countries such as Brazil, Malaysia and Indonesia become competitive in the US and EU markets. This releases land for food production in both countries leading to a rise in food exports from the US and EU, as shown in Table 9.

Free trade enables MICs to produce more biofuels. More food production occurs in the high quality lands in the mandated countries. Indirect emissions increase in the MIC nations because of increased biofuel production.

The decrease in the cost of second gen biofuels reduces the opportunity cost of land, which in turns lowers food prices and inducing more food consumption. MICs produce more food and biofuels, which leads to enhanced land-clearing. This result is somewhat surprising since *ex ante*, one may think that the lower cost of second generation biofuels will lead to less land conversion and overall emissions. Due to a decrease in the cost of second gen biofuels, the scarcity rent of oil declines but only marginally.[50] Indirect carbon emissions almost double as shown in Table 10. Total emissions increase sharply.

[50] This is analogous to a decline in the backstop price in a nonrenewable resource model.

Exogenous improvements in biotechnology reduce food prices by about 12% compared to the REG model. The demand for land declines. Because of increased food production, US food exports rise by about 150% in 2025. Less land is required to produce the regulated level of biofuels. Indirect emissions decline significantly in this case. In summary, the only parameters that have a major effect in increasing aggregate emissions are the removal of trade barriers and lower cost of second gen fuels.

Aggregate discounted net surplus is found to be rather insensitive to changes in model assumptions. However, the implicit biofuel subsidies are far more sensitive, especially to a change in the initial oil reserves and higher yields from biotechnologies. A reduction in the initial oil reserve causes a 26% and 70% reduction, respectively, in the US subsidy on first and second generation biofuels. A lower oil stock increases the price of gasoline and improves the competitiveness of biofuels. Hence, the subsidy needed to meet the mandate is lower. An increase in agricultural yields due to improvements in biotechnology causes a 25-35% reduction in the subsidy on first and second gen biofuels. Increase in agricultural yields reduces the shadow price of land, which increases the competitiveness of first gen biofuels.

Changes in the values of the parameters have a major impact in increasing biofuels production in the MICs, even more than on domestic production in the US and EU. Lower initial oil reserves and increased agricultural yields, both raise MIC biofuels production by about 25% (Table 9). The reason MICs are impacted is because they have surplus cultivable land. The US and EU do not. Relative changes in food and fuel prices, and land rents affect imports to the US and EU, mainly from the MICs. They do not affect domestic consumption in the US/EU in a big way.

Additional Runs: Sensitivity to Other Mandates, Oil Prices and Dietary Preferences

It may be useful to comment on how the BASE model (the one without regulation) itself changes due to the changes in the above parameters. The most important observation is that when the conversion cost of new land decreases, direct emissions decline, because more biofuel is used. Less food is consumed but greater biofuel use leads to more land conversion. Other factors, such as removal of trade barriers and decrease in the cost of second generation fuels, have similar qualitative effects on the model without regulation, but less in magnitude.[51]

We also consider the case of China and India, the two most populous countries, imposing domestic biofuel mandates.[52] In this scenario, we assume that these two nations impose a mandate requiring the share of biofuels in transportation to rise linearly to at least 10% by 2025. Imposing these mandates increases biofuel consumption in the MICs from 10 billion gallons under REG to 24 billion. But terms of trade effects in the MICs is smaller now because the two countries use more biofuels. However, global oil consumption goes down by less than 1%, with little change in direct carbon emissions in the MICs. What is interesting is that instead of moving land away from food to fuel production, farmers from MICs which are land abundant bring new land under cultivation (another 140 million hectares). This is a nearly six fold increase in land conversion – the original increase in MIC land use due to energy regulation was only 24 million hectares (see Fig.7). As a result, indirect emissions almost double to 12 million tons. But world food prices still rise by only 2% beyond the impacts from US and EU mandates.

We also run simulations to estimate the effects of two key assumptions in the model. First, we suppose that the price of oil remains constant over the entire time period at $79/barrel, the initial crude oil price in our model. Without a mandate, world use of biofuels decreases because of constant oil prices. US biofuel use drops from 7.2 to under 3 billion gallons. Second gen fuels are never adopted. Because of the mandate, indirect carbon emissions increase by more than 60% compared to the BASE model (both with cheap oil). About 50 million hectares of new land is brought under cultivation because of energy regulation. This is double the increase in acreage relative to when oil prices rise competitively. With cheap oil, biofuel use is low without mandates and increases sharply with them. Now, imposing the mandate has a bigger effect on food prices, which increase by 12% - recall that food prices increased by about 5% when oil prices were allowed to increase competitively. The mandates induce higher land conversion to energy and

[51] Detailed results for this case are not shown but can be obtained from the authors.
[52] The number of vehicles in China is expected to increase from 30 to 225 million by the year 2025, and in India from 15 to 125 million (IEA 2009). Currently, biofuels supply less than 1% of transportation fuel in these countries. There is some evidence that both countries are actively considering imposing biofuel regulation (Eisenstraut, 2010).

less to food. The subsidy required to meet the US targets is almost twice larger than under the REG model.

Second, we examine what happens when food preferences are assumed to be constant, i.e., there is no income-driven preference for meat and dairy products. We fix income elasticities for meat and cereal products in the MICs and LICs at levels similar to US and EU. This means that people in developing countries are assumed to have the same elasticities towards meat and cereals as in developed nations, but at their lower consumption levels. As a result, their meat consumption increases much less rapidly with income than before. To compare, note that per capita meat consumption goes up from 78 to 95 kg during 2010-25 when preferences change endogenously as in all the previous runs. When preferences are kept fixed, they only rise to 84 kg. Food prices increase over time by about 6% in the same period, compared to 13% in the BASE model (see Table 4). Since land rents fall, more biofuels are produced – three billion gallons more than in the BASE case. In 2025, food prices are higher under regulation by only 2.5% compared to no regulation, when preferences are assumed stationary. To meet their biofuel targets, US and EU import less biofuels from MIC countries. MIC nations convert less land to farming.

5. Concluding Remarks

We model the effect of biofuel mandates in the US and EU by combining three elements which have not been considered in previous studies - income-driven dietary preferences, differences in land quality and a limited endowment of oil. We find that food price increases will come primarily from population growth and dietary changes towards meat products. Roughly about two thirds of the price increase comes from demand growth, and about a third from energy mandates. This is contrary to several studies which suggest that energy mandates will lead to significant food price increases and world hunger (New York Times, 2008).

The energy mandates mostly help accelerate conversion of medium quality lands which are currently under grasslands and forest cover, and largely located in developing countries. Sensitivity analysis shows that even when the big countries such as China and India adopt mandates, the additional supply comes from new land conversion, not so much by displacing food production. This trend is robust across many different scenarios. The good news is that the impact on food prices is likely to be small. The bad news is that the effect of the mandates on indirect carbon emissions may be large and likely to offset any emission declines from replacing gasoline in transportation, an outcome widely feared by the policy community (Searchinger *et al.,* 2008).

Another key insight from the model is the effect of oil supplies. New discoveries of oil and lower oil prices will mean lower impacts on food production, less land conversion but more direct carbon emissions from combustion. Scarce oil and higher prices will imply biofuels become more competitive, hence bigger effects on food prices, more land conversion and larger indirect emissions from land-use changes. In one case, direct emissions go up, in the other case, indirect emissions increase. Either way, biofuel mandates are not likely to reduce carbon emissions and might increase them somewhat.

These results arise from a modeling strategy that allows for endogenous land allocation and the dynamic effects of exogenous income growth on preferences for meat and dairy products. If these effects are not taken into account, then econometric models may overestimate the role of energy mandates in determining food prices. In our model, food price increases result in more land conversion. Models that have found large impacts of biofuel policies often do not take into account the supply response to price.

The model is simple and can be extended in many directions. From the sensitivity analysis, it seems that energy prices have a major impact on biofuels supply. Thus more work needs to be done in studying the effect of energy price changes, especially at the level of individual behavior, e.g., the choice of fuel-efficient cars. High oil prices may lead to new discoveries and therefore reduce substitution to biofuels. Learning effects, that are a result of market share, especially for new technologies like second generation biofuels, may be quite significant. Newer technologies for hybrid and alternate fuel vehicles may mean increased efficiency in the transportation sector which in turn will impact biofuel use. Finally it is not clear how other countries will react to these biofuel mandates in choosing their own energy and agricultural policies. Although we consider the case of China and India imposing mandates of their own, these strategic effects could be modeled explicitly in future work. Alternatively, the international climate negotiations may lead to a price on carbon, which will then imply that countries that encroach upon grass and forest cover to grow energy crops will have to face higher abatement costs. This may reduce biofuel production and indirect carbon emissions.

Even if food price increases occur, whether from demand effects of energy policies, they may lead to increased efficiency in agriculture, such as irrigation, better seeds and other inputs. Our model assumes certain rates of technological change, but they are not linked to prices. This may further strengthen the supply response outlined in the paper. Another major issue not addressed directly in the paper is how food price increases may affect the poor. The price increases, even if modest may have major impacts in terms of increasing poverty and malnutrition in the low and medium income economies, which is home to large numbers of the very poor. This issue needs to be addressed further in future research, with data on the price-induced behavior of consumers at various income levels.

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APPENDIX: DETAILS OF THE EMPIRICAL MODEL

Here we describe the empirical model in more detail. Notice that all variables are functions of time, but for convenience we omit the time index when necessary. In what follows, the regional index is also omitted whenever convenient.

The model is a discrete-time, non-linear dynamic programming problem and was solved using GAMS software. Since we consider a Hotelling model, the scarcity rent can be positive if and only if the oil stock is exhausted over the entire planning horizon. Thus the model is run for the period 2005-2205. It reaches a steady state around 2100. To reduce computational time, it is programmed in time steps of 5 years. The reference year for model calibration is 2005.

Demand Demand for cereals and meat are assumed to be independent as in other studies (Rosegrant et al. (2001), Hertel *et al.* (2008a)). Cereals include all grains, starches, sugar and sweeteners and oil crops.[53] Meat includes all meat and products and dairy such as milk and butter. Demand functions are given by equation (1). Demand for food products (cereal, meat) and fuel is in billion tons and billion gallons, respectively. The constant demand parameter A_l is product and region specific. It is computed using the regional per capita income, population, demand for each product and the world price of the product in the base year (2005). For example, for cereal demand in the US in year 2005, US per capita income is $42,040, population 280 million, per capita demand for cereals is 0.24 tons and the initial price and income demand elasticities are -0.05 and 0.06. The price for cereals is $170/ton. From equation (1), the constant parameter is calculated as 0.000489. Other demand parameters are computed similarly.

All the data needed to calculate the constant demand parameters are shown in Table A1. Initial per capita income is taken from the World Bank database (World Bank 2010a) and population from UNDP (2004). Per capita demand for cereals and meat are from FAOSTAT which also gives per capita demand for the US and EU. However, we aggregate per capita demand for MICs and HICs. We calculate their weighted average per capita demand, where the weight is the share of the country population in the region. Initial per capita demand for transportation fuel is computed by aggregating diesel and gasoline consumption for each region. For the US, EU, MICs and LICs, these data are readily available from WRI (2010). However, for the region Other HICs, they had to be aggregated from individual country data.

[53] These categories are from the FAO (see FAOSTAT). Grains account for about half of all crop land followed by oil, crops (20%) and starches (5%).

Table A1. Demand parameters in base year (2005)

		USA	EU	Others HICs	MICs	LICs
Per capita income	(2005$ per capita/yr)	42,040	36,000	34,000	7,050	1,500
Population	(millions)	280	460	180	4,555	760
Per capita demand	**Cereals** (tons/cap/yr)	0.25	0.24	0.22	0.20	0.20
	Meat (tons/cap/yr)	0.40	0.31	0.30	0.07	0.030
	Fuel (gallon/cap/yr)	500	140	150	30	10
Price	**Cereals** ($/ton)	175	175	175	175	175
	Meat ($/ton)	1,800	1,800	1,800	1,800	1,800
	Fuel ($/gallon)	2.50	2.80	2.60	2.60	2.60
Income elasticity	**Cereals**	+0.06	+0.13	+0.14	+0.30	+0.40
	Meat	+0.61	+0.51	+0.57	+0.90	+1.20
	Fuel	+0.90	+0.95	+1.00	+1.20	+1.30
Price elasticity	**Cereals**	-0.05	-0.11	-0.10	-0.37	-0.40
	Meat	-0.50	-0.55	-0.60	-0.80	-0.90
	Fuel	-0.30	-0.40	-0.45	-0.70	-0.70
Constant	**Cereals**	0.000489	0.002010	0.001313	0.000465	0.000243
	Meat	17.9518	134.7235	42.2175	629.9936	99.8273
	Fuel	0.048102	0.009919	0.007232	0.001560	1.218652

Notes: 1) Per capita income is in 2005 dollars; 2) Population in billions; 3) Per capita demand for cereals and meat in kg/cap/year; Per capita demand for fuel in gallon/cap/year; 4) World cereal and meat prices are weighted average prices calculated from World Bank (2007); US fuel price taken from USDOE; Other HIC, MIC and HIC fuel prices are world weighted averages.

Since cereals and meat are internationally traded, their world prices are reported in Table A1. These data are weighted averages for the base year. But transportation fuels are consumed and produced domestically so their price is region-specific.

Price and income elasticities for cereals, meat and fuel products are given by Hertel *et al.* (2008a). Elasticities for the US are directly available. However, we need to aggregate the demand elasticities for other regions, namely the EU, Other HICs, MICs and LICs. To illustrate our procedure, suppose we need to compute the cereal demand for a region with only two countries. We use the per capita demand for cereals, world cereal prices, population and price and income elasticities for each country to compute the demand curve for cereals for each country, which is aggregated up to get the demand function for the region. The aggregate demand function yields the price and income elasticity of demand. Thus, the regional demand elasticity for cereals is the weighted average elasticity where the weight is the share of country consumption in regional consumption. These aggregated initial values of the elasticities are reported in Table A1.

Demand for food products and for blending fuel are exogenously driven by the growth in per capita income and population. Per capita income information is from Nordhaus and Boyer (2000) and world population figures are from UNDP (2004). Table A2 shows the level of per capita income and population by region in 2005 and 2050. Since our model is calibrated in time steps of five years, annual growth rates of population and per capita income are constant within each five year period.

Table A2. Population and per capita income in 2005 and 2050

	Population (millions)		**Per capita income** (2005$/capita)	
Region	2005	2050	2005	2050
US	280	312	42,040	57,767
EU	460	523	36,000	49,468
Other HICs	180	201	34,000	46,720
MICs	4,555	6,381	7,050	25,000
LICs	760	1,778	1,500	7,000
World	6,235	9,185	--	--

The AIDADS (An Implicit Direct Additive Demand System) is the most flexible demand function that takes into account the change in dietary habits towards meat products as the level of income rises. However, there are no studies that provide the parameters of this function for cereal and meat products for different regions.[54] We circumvent this problem by making some adjustments in the calibration of the demand function given by (1). First, the change in dietary habits is driven by the rise in per capita income. As a result, we consider the per capita income and not the global income (per capita income times population) as in Rosegrant *et al.* (2008). Second, we introduce flexibility in the diet composition by letting income elasticities vary exogenously with the level of income. We use Hertel *et al.* (2008b) which gives a detailed database on the elasticities for cereals and meat for all countries. For each country, we relate the per capita income from the World Bank database (2010a) to the elasticity for cereals and meat. We apply this procedure for all cereals and meat elasticities. Table A3 illustrates how income elasticities change with the level of income (see numbers in bold). In the year 2050, per capita income in the LICs converges to that of MICs in year 2005. As a result, LIC income elasticities in 2050 are quite similar to MIC income elasticities in 2005.

Energy Primary energy is provided by three resources - gasoline, first gen and second gen biofuels indexed

[54] Cranfield *et al.* (2002) estimate consumer demand patterns for different groups of products (food, beverages and tobacco, gross rent and fuel, household furnishings and operations and other expenditure) using the AIDADS demand system. Unfortunately his classification is not useful for our analysis of preferences over cereals and meat.

Table A3. Changes in income elasticities for food products conditional on per capita income

Region	Year	Per capita income ($/capita)	Cereals	Meat
US	2005	42,040	+ 0.06	+ 0.61
	2050	57,767	+ 0.05	+ 0.59
EU	2005	36,000	+ 0.09	+ 0.51
	2050	49,468	+ 0.06	+ 0.49
Other HICs	2005	34,000	+ 0.07	+ 0.57
	2050	46,720	+ 0.06	+ 0.55
MICs	**2005**	**7,050**	**+ 0.30**	**+ 0.90**
	2050	25,000	+ 0.20	+ 0.70
LICs	2005	1,500	+ 0.40	+ 1.20
	2050	**7,000**	**+ 0.30**	**+ 0.90**

by $\{g, bf, bs\}$. Each region is endowed with an initial stock of oil $\bar{X}$. Data on stocks is taken from the World Energy Council (WEC 2007) and reported in Table A4. Oil is also an input in sectors other than transportation, such as in chemicals and heating. Studies (IEA 2009a) suggest that 50% of oil consumption is in transportation. So we only consider 50% of total oil reserves as the resource stock available for transport. [55,56]

Table A4. Extraction cost parameters for oil

Available stock (trillion barrels)	**Extraction cost parameters** ($US/barrel)		
	ϕ_1	ϕ_2	ϕ_3
4.26	20	100	5

Let $x(t)$ be the amount of oil used globally at period *t* and X(t) the oil stock *in situ* at period *t* . Then, the change in the remaining oil stock is given by $X(t+1) - X(t) = -x(t)$. To take into account the heterogeneity of oil reserves, extraction costs in period θ depend on the cumulative quantity of oil extracted. As discussed in the paper, unit extraction costs are given by (4) in which the parameter ϕ_1 is the extraction cost over the base period, and ϕ_2 and ϕ_3 are calibrated parameters reported in Table A4. Oil is converted into gasoline using a constant coefficient of 0.3 and a cost of conversion of $0.5/gallon (Chakravorty *et al.* 2010). Due to technological progress, the latter cost is projected to decrease annually by 1.5%.

[55] By keeping the share of oil in transportation fixed, we ignore possible changes in the share of petroleum that goes to the transportation sector. It is not clear *ex ante* how the share of oil in transportation will change as the price of oil increases, and the answer may depend on the availability of substitutes in transport and other uses.
[56] In the paper, we discuss the effect of an exogenous change in oil reserves on our results.

Energy supply Transportation energy is supplied by gasoline and biofuels in a convex linear combination given by (3), where λ is a constant, μ_g the share of gasoline, ρ the elasticity of substitution, and q_g, q_{bf} and q_{bs} are the respective input demands for gasoline, first gen and second gen biofuels. The parameter λ is region specific. It has been calculated from equation (3) by using regional fuel demand (q_e), the observed share of gasoline (μ_g), regional demand for gasoline (q_g), for biofuels (q_{bf}) and the elasticity of substitution (ρ). Table A5 presents the data used in calibration for base year (2005).

Table A5. Energy supply parameters by region

	USA	EU	Others HICs	MICs	LICs
Blending fuel use q_e (billion gallons)	140	64	27	136	8
Gasoline use q_g (billion gallons)	134	62	26	130	7.8
Gasoline share θ_g (Gasoline use/Transportation fuel)	0.96	0.97	0.97	0.96	0.98
Biofuels use q_{bf} (billion gallons)	7	3	1	5	0.5
Elasticity of substitution ρ	2	2	2	1.85	1.50
Constant λ	1.068	1.049	1.058	1.072	1.043

Sources: 1) Transportation fuel consumption (WRI 2010); 2) Biofuels consumption (FAPRI 2010, FAO 2008a) is the sum of ethanol and biodiesel use. 4) Share of gasoline and biofuel consumption in transportation is computed from observed data. The elasticity of substitution is taken from Hertel et al (2008a).

Aggregate consumption of transportation fuel is the per capita demand given in Table A1 multiplied by population.[57] Gasoline consumption for transport is available from Energy Balances (IEA 2008). Figures for the US and EU are directly available. For the other regions, we aggregate consumption for each member country. To calculate biofuel consumption, we only consider first-generation biofuels since the consumption of second generation biofuels is negligible. Since transportation fuel use does not change markedly from year to year, we use figures for 2005. However biofuel consumption exploded after 2005.[58] If we had calibrated the CES production function for the base year 2005, the share of biofuels in transportation fuel would have been very low (e.g., less than 2% in the EU) and it would have prevented the growth of biofuel consumption in the model. We thus use the more realistic consumption data for 2007 for biofuels instead of 2005. This results in overestimating biofuel consumption in Other HICs and LICs which evens out over the longer term.

[57] Transportation fuel is domestically refined and it is not traded, but crude oil is a traded commodity.
[58] During 2005-2007, world biofuel production rose from 8.7 to 13.2 billion gallons. Before 2005, Brazil accounted for most of the world's consumption. US and EU biofuel use increased after 2005 mainly because of regulation but also due to high crude oil prices.

Land Quality The USDA database divides the global land area into nine land categories based on climate and soil properties (Eswaran *et al.* 2003) labeled I to IX (see Figure 3). They are classified according to their suitability for agricultural production, category I being the most productive. Land classes unsuitable for agricultural production, i.e., categories VII to IX are disregarded in our study. We aggregate the remaining six (I through VI) based on their characteristics. Category I and II are grouped and referred to as land class 1 in the paper, III and IV as class 2, and V and VI as class 3. We thus have three land classes indexed $i = \{1, 2, 3\}$. Land class 1 benefits from a long growing season and soil of high quality, class 2 has a shorter growing season due to water stress or excessive temperature variance. Class 3 is of the lowest quality. Initial acreage available for each land class can be divided into cultivated land ($\overline{L}_i$) and marginal land (L_i^s). Cultivated lands may be allocated to different uses indexed by *j* which denote food crops, first-gen or second-gen biofuels. Cultivated land area can be increased by bringing marginal lands under production**.** Total available marginal land equals 1.6 billion hectares (FAO 2008a). Forests under plantations or under legislative protection are not included in the model. The parameters for land conversion costs, given by (2) are $\phi_1 = 30$ and $\phi_2 = 1.5$. They are assumed to be the same across land class and region.[59] Then, we have $L_i^s(t+1) - L_i^s(t) = -l_i^s(t)$. In any period θ, the land available for agricultural production is given by $\overline{L_i} + \sum_{t=0}^{\theta} l_i^s(t)$. The land allocation constraint is defined by $\overline{L_i} + \sum_{t=0}^{\theta} l_i^s(t) - \sum_j L_i^j \geq 0$, where L_i^j is the acreage from land class *i* allocated to use *j*. The Lagrange multiplier associated with this constraint is the implicit land rent. Total supply is the product of land supplied times its yield.[60]

Cultivated land may be allocated either to food crops, to first-generation or second-generation biofuels. For each use, we need to obtain yield data by land class. Each land class is characterized by a group of countries and FAOSTAT gives crop yields for each country. We match USDA and FAOSTAT data by country. To calculate food crop yields, we use information on different crops: cereals, starches, sugar and sweeteners and oil crops. Food crop yield with respect to each land class is a weighted average; the weight is the share of crop in production. The values are presented in Table A6.

[59] We examine the sensitivity of the results to a 50% reduction in the land conversion cost, i.e., we reduce the value of φ_1 by half and keep φ_2 constant.
[60] Since our model is coded in time steps of five years and harvests are annual, we multiply the production function $k_i^j L_i^j$ by the number of time periods (5 years).

Table A6. Yields by Land Class and Region

	Land class	US	EU	Other HICs	MICs	LICs
Initial crop yields	1	4.0	4.0	4.0	3.5	2.5
(tons/ha)	2	2.5	2.0	2.2	2.0	1.5
	3	1.7	1.7	1.7	1.0	0.7
Annual growth in	1	0.9	0.9	0.9	1.2	1.1
crop yields	2	0.7	0.7	0.7	1.0	0.8
(% change)	3	0.6	0.6	0.6	0.8	0.7

Source: Average annual growth rates adapted from Rosegrant *et al.* (2001).

To determine the first gen biofuel yield by land class, we proceed in two steps. These biofuels are produced from a specific crop in each region (see Table 3), e.g., sugar cane in MICs and rapeseed in EU. As a first step, for each land class we determine the crop yield used to produce these biofuels. Second, we use the coefficient of conversion for crops to biofuels (given by Rajagopal and Zilberman 2007). The yields are reported in Table A7. Information on second gen biofuels is scarce. Yields are assumed uniform across land classes. This assumption is reasonable because second-gen biofuels are less demanding in terms of land quality than first gen biofuels (Khanna 2008). Recall that 2,000 gallons per hectare are produced from ligno-cellulosic whereas 1,000 gallons per hectare are produced from Biomass-to-liquids (BTL).

Table A7. Yields for first generation biofuels[61]

	US	EU	Other HICs	MICs	LICs
Representative crop Crop type	Corn	Rapeseed[3]	Corn	Sugar-cane	Cassava
Energy yield per land class[2] (gallons/hectare)					
Land class 1	800	400	800	1,700	600
Land class 2	500	300	500	1,500	400
Land class 3	200	200	200	1,200	300

Total production costs are from the GTAP database 5 for the year 1997.[62] Information on total production costs is directly available for the US and EU. However, we need to aggregate production costs for other regions (Other HICs, MICs and LICs). The GTAP database divides the total costs into intermediate inputs,

[61] Only part of the plant (the fruit or the grain) is used to produce first-generation biofuels. The rest of the plant is used to produce other by-products. For instance, crushed bean "cake" (animal feed) and glycerine are by-products of biodiesel. For rapeseed-biodiesel and corn-ethanol, the revenue from the sale of co-products *decreases* their production cost by about a third (FAO 2008a).

[62] We did not have access to more recent data from GTAP.

skilled and unskilled labor, capital, land and taxes. Using equation (3), we can calculate the cost parameters by using total production costs and total production. They are reported in Table A8.

Table A8. Crop production cost parameters by region

	US	EU	Other HICs	MICs	LICs
η_1	1.51	1.61	1.55	0.37	0.80
η_2	1.50	1.55	1.50	1.60	1.70
Unit initial production cost (US$/ton)	110	120	120	140	150

Food crops can be used directly for food (i.e., cereals) or animal feed that is transformed into meat. We assume that one ton of primary crop produces 0.85 tons of the final food product (FAOSTAT). It is taken to be uniform across regions.[63] The quantity of meat produced from one ton of crop is referred to as *the feed ratio* which is the amount of feed used per unit of meat. It is region-specific and adapted from Bouwman (1997). We use a feed ratio of 0.4 for developed countries (US, EU and Other HICs) and 0.25 for developing countries (MICs and LICs) to account for higher conversion efficiencies in the former.

Carbon emissions The model tracks direct as well as indirect carbon emissions. Emissions from gasoline are the same across regions, but emissions from first and second gen biofuels are region-specific and depend on the crop used. Emissions from gasoline occur at the consumption stage, while emissions from biofuels occur at the production stage. Let z_g represent the amount of carbon (measured in tons of CO_2) released per unit of gasoline consumed, and z_{bf} and z_{bs} are emissions per unit first and second gen biofuels. The figures used are shown in Table A9. Finally, indirect carbon emissions are generated by conversion of marginal lands, namely forests and grasslands into food or energy crops. The sequestered carbon is released back into the atmosphere. Let z_i^s be the amount of carbon released in any region per unit of land of class *i* brought into production. Then, aggregate indirect carbon emissions are given by $z_i^s l_i^s$.

Indirect emissions depend on whether forests or grasslands are being converted for farming - one hectare of forest releases 604 tons of CO_2 while grasslands emit 75 tons (Searchinger *et al.* 2008).[64] For each land class and region, we weight the acreage converted by the share of marginal lands allocated to each use

[63] Other models make similar assumptions (e.g., Rosegrant *et al.* 2001).
[64] Losses from converting forests and grasslands are assumed to be the same in MICs and LICs. Carbon is sequestered in the soil and vegetation. About a quarter of the carbon is lost from the soil and the rest from vegetation. Detailed assumptions behind these numbers are available in the supplementary materials to Searchinger *et al*. (2008) available at: http://www.sciencemag.org/content/suppl/2008/02/06/1151861.DC1/Searchinger.SOM.pdf.

(grasslands or forests). For instance, in the MICs, 55% of land class 2 is under pasture (45% under forest), thus indirect emissions from converting one hectare of land class 2 are 313 tons of CO_2 per hectare.[65] Land class 3 has 84% forest, so emissions are 519 tons/ha. The corresponding figures for LICs are 323 tons (land class 2) and 530 tons (class 3).

Table A9. Carbon emissions from gasoline and representative biofuels

	Gasoline	**Corn ethanol**	**Rapeseed biodiesel**	**Sugar-cane ethanol**	**Cassava ethanol**
Carbon emissions (tons of CO_2/gallon)	0.0117	0.0062	0.0062	0.0014	0.0062
Emission reductions relative to gasoline	-	53%	53%	80%	53%

Source: Gasoline, corn ethanol and sugar-cane ethanol figures are from Farell (2006), rapeseed biodiesel from IEA (2009b)

[65] By using this method, we assume that the share of marginal land under forests and grasslands is constant. In our model, the area of marginal land converted into cropland is endogenous; however, we cannot determine if forests or grasslands have been converted.

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